

New limits on 2β processes in ^{106}Cd

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Abstract. A radiopure cadmium tungstate crystal scintillator, enriched in ^{106}Cd to 66%, with mass of 216 g ($^{106}\text{CdWO}_4$) was used in coincidence with four ultra-low background HPGe detectors contained in a single cryostat to search for double beta (2β) decay processes in ^{106}Cd . New improved half-life limits on the 2β processes in ^{106}Cd have been set on the level of $10^{20} - 10^{21}$ yr after 13085 h of data taking deep underground (3600 m w.e.) at the Gran Sasso National Laboratories of INFN (Italy). In particular, the limit on the two neutrino electron capture with positron emission, $T_{1/2}^{\varepsilon\beta^+2\nu} \geq 1.1 \times 10^{21}$ yr, has reached the region of theoretical predictions. The resonant neutrinoless double electron captures to the 2718, 2741 and 2748 keV excited states of ^{106}Pd are restricted on the level of $T_{1/2}^{2\varepsilon 0\nu} \geq (8.5 \times 10^{20} - 1.4 \times 10^{21})$ yr.

1. Introduction

While we already know from experiments on neutrino oscillations that ν 's have non-zero masses, their absolute values are unknown because these investigations are sensitive only to differences in ν mass squares [1]. Experiments on neutrinoless (0ν) double beta (2β) decay of atomic nuclei $(A, Z) \rightarrow (A, Z \pm 2) + 2e^\mp$ are considered to-date as the only reliable way to find the mass absolute scale and to study the neutrino properties (are they Majorana, $\nu = \bar{\nu}$, or Dirac, $\nu \neq \bar{\nu}$, particles). This process is related also with other effects beyond the Standard Model (SM), like possible existence of right-handed currents in weak interaction, Majorons, etc. In spite of searches for $2\beta 0\nu$ decay during near 70 years, it is still not surely observed, with half-life sensitivities of $\simeq 10^{25}$ yr for $(A, Z) \rightarrow (A, Z + 2)$ and $\simeq 10^{21} - 10^{22}$ yr for $(A, Z) \rightarrow (A, Z - 2)$ processes reached in the best experiments. Two neutrino (2ν) mode of 2β decay (process allowed in the SM) was already observed in more than 10 nuclides with $T_{1/2} \simeq 10^{18} - 10^{24}$ yr; see the last reviews [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14] and refs. therein.

^{106}Cd is one of the best candidates to search for processes $(A, Z) \rightarrow (A, Z-2)$: double positron emission ($2\beta^+$), electron capture with positron emission ($\varepsilon\beta^+$) and two electron capture (2ε) because of its high decay energy ($Q_{2\beta} = 2775.39(10)$ keV [15]) and comparatively high natural abundance ($\delta = 1.25(6)\%$ [16]). Investigations of $2\beta^+/\varepsilon\beta^+/2\varepsilon$ processes could clarify question about possible contribution of right-handed admixtures in the weak interaction to $2\beta 0\nu$ decay probability [17]. ^{106}Cd nucleus is interesting also because of possible resonant $2\varepsilon 0\nu$ captures to excited levels of the daughter nucleus ^{106}Pd which could be enhanced by few orders of magnitude because of proximity of the released energy to energy of one or more of the excited levels [6, 18].

In recent searches for 2β decay of ^{106}Cd , 32 planar HPGe detectors and 16 thin ^{106}Cd metallic foils between them were used in the TGV-2 experiment [19], and array of CdZnTe room temperature semiconductors was used in the COBRA studies [20]. At the first stage of our investigations [21], $^{106}\text{CdWO}_4$ crystal enriched in ^{106}Cd to 66% with mass of 216 g was used as a scintillating detector. At the second stage, described here, it is operated in low background set-up together with four HPGe detectors enhancing sensitivity to some 2β processes with emission of γ quanta. We report here preliminary results of the experiment.

2. Experimental set-up and measurements

The $^{106}\text{CdWO}_4$ scintillator ($\varnothing 27 \times 50$ mm, mass 216 g) was grown from deeply purified Cd (66% of ^{106}Cd) by the Low-Thermal-Gradient Czochralski method [22]. It was optically connected to a low-background photomultiplier tube (PMT, Hamamatsu R6233MOD) through a radiopure PbWO_4 crystal light-guide ($\varnothing 40 \times 83$ mm) produced from deeply purified archaeological lead that allowed to suppress radioactivity from PMT. The detector was installed in an ultra-low background GeMulti HPGe spectrometer at the Gran Sasso underground laboratory (LNGS) of the INFN (Italy) at the depth 3600 m w.e. Four HPGe detectors (with volumes approximately 225 cm^3 each) were mounted in one cryostat with a well in the centre. An event-by-event data acquisition system stored the time of arrival of the events in the $^{106}\text{CdWO}_4$ and HPGe detectors, and the pulse shape of $^{106}\text{CdWO}_4$ scintillation signals. The $^{106}\text{CdWO}_4$ and HPGe detectors were calibrated with ^{22}Na , ^{60}Co , ^{137}Cs and ^{228}Th . The energy resolution of the $^{106}\text{CdWO}_4$ detector can be described by the function: $\text{FWHM} = \sqrt{21.7 \times E_\gamma}$, with FWHM and E_γ in keV. The energy resolution of the HPGe spectrometer is $\simeq 2.0$ keV for the 1332 keV γ quanta of ^{60}Co . More details are given in [23].

The data were accumulated during 13085 h. The pulse-shape discrimination based on the mean time of the scintillation signal [24] was applied to discriminate events caused by γ and β particles from those induced by α 's. Fig. 1 (left) shows $^{106}\text{CdWO}_4$ energy spectra: in anticoincidence with HPGe detectors; in coincidence when energy release in at least one of the HPGe detectors is > 200 keV; and in coincidence when $E(\text{HPGe}) = 511 \text{ keV} (\pm 3\sigma)$, where σ is the energy resolution of the HPGe detectors at 511 keV).

3. Results and discussion

Contributions of possible radioactive sources to the collected spectra were simulated with the EGS4 code [25]. The list includes, in particular, radioactive contaminations of the $^{106}\text{CdWO}_4$ crystal scintillator [21], external γ quanta from the PMT and materials of the set-up, and also $2\beta 2\nu$ decay of ^{116}Cd present in the $^{106}\text{CdWO}_4$ crystal on the level of 1.5% [22]. Fit of the $^{106}\text{CdWO}_4$ anticoincidence spectrum by the background model, and its main components are shown in Fig. 1 (right).

Response of the $^{106}\text{CdWO}_4$ scintillator to different modes of 2β decay of ^{106}Cd to the ground state and excited levels of ^{106}Pd were also simulated with the EGS4; initial kinematics of particles emitted in decay and deexcitation of the daughter nucleus was given by the DECAY0 event generator [26]. In general, we did not find any peculiarities in the data accumulated with the $^{106}\text{CdWO}_4$ and HPGe detectors that could be ascribed to the 2β processes in ^{106}Cd . Thus we

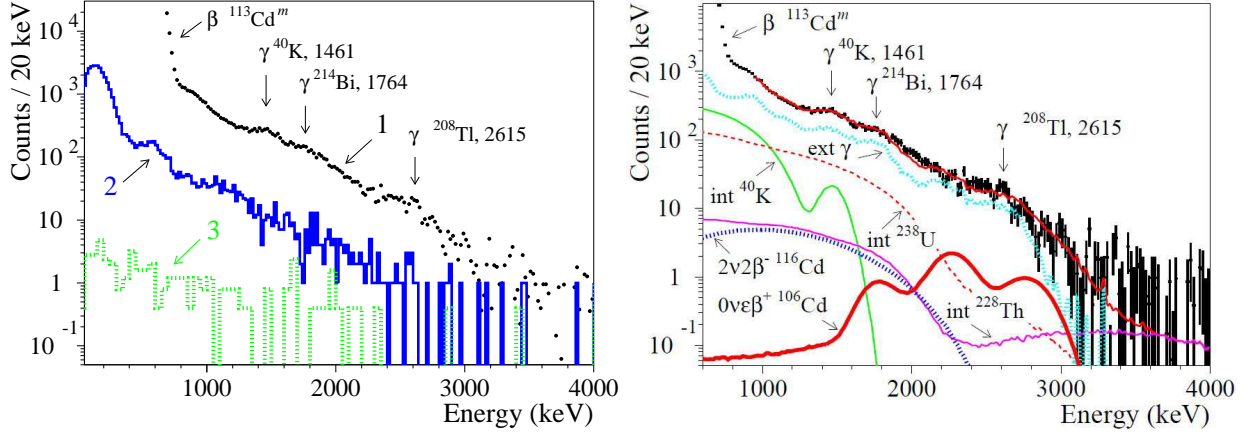


Figure 1. Left: $^{106}\text{CdWO}_4$ energy spectra collected during 13085 h: 1 – in anticoincidence with HPGe detectors; 2 – in coincidence when energy release in at least one of the HPGe is > 200 keV; 3 – in coincidence when $E(\text{HPGe}) = 511(\pm 3\sigma)$ keV. Right: Fit of the anticoincidence spectrum by background model (red continuous line), and its main components. The excluded distribution of the $\varepsilon\beta^+0\nu$ decay of ^{106}Cd to the ground state of ^{106}Pd with $T_{1/2} = 1.5 \times 10^{21}$ yr is shown too.

give only the half-life limits according to a formula: $\lim T_{1/2} = \ln 2 \cdot N \cdot \eta \cdot t / \lim S$, where N is the number of ^{106}Cd nuclei in the $^{106}\text{CdWO}_4$ crystal ($N = 2.42 \times 10^{23}$), η is the detection efficiency, t is the time of measurements, and $\lim S$ is the number of events of the effect searched for, which can be excluded at a given confidence level (C.L.).

We have analyzed different data to estimate limits on the 2β processes in ^{106}Cd . For instance, to derive the value of $\lim S$ for the $\varepsilon\beta^+0\nu$ decay of ^{106}Cd to the ground state of ^{106}Pd , the $^{106}\text{CdWO}_4$ anticoincidence spectrum was fitted by the model built from the components of the background and the effect searched for. The best fit, achieved in the energy interval 1000 – 3200 keV, gives the area of the effect $S = 27 \pm 49$ counts, thus providing no evidence for the effect. In accordance with the Feldman-Cousins procedure [27], this corresponds to $\lim S = 107$ counts at 90% C.L. Taking into account the detection efficiency within the interval given by the Monte Carlo simulation (69.3%) and the 95.5% efficiency of the pulse-shape discrimination to select γ and β events, we got the half-life limit: $T_{1/2} \geq 1.5 \times 10^{21}$ yr. The excluded distribution of the $\varepsilon\beta^+0\nu$ decay of ^{106}Cd to the ground state of ^{106}Pd is shown in Fig. 1 (right).

The counting rate of the $^{106}\text{CdWO}_4$ detector is substantially suppressed in coincidence with the energy 511 keV in the HPGe detectors. The coincidence energy spectrum of the $^{106}\text{CdWO}_4$ detector is presented in Fig. 2 (left). There are only 115 events in the energy interval 0.05 – 4 MeV, while the simulated background model (built by using the parameters of the anticoincidence spectrum fit) contains 108 counts. We have estimated values of $\lim S$ for the 2β processes in ^{106}Cd in different energy intervals. Some of the excluded distributions are presented in Fig. 2 (left); corresponding $T_{1/2}$ limits are given in Table 1. In particular, the half-life limit on the $\varepsilon\beta^+2\nu$ decay is equal $T_{1/2} \geq 1.1 \times 10^{21}$ yr. This value is close to theoretical predictions of [29] where $T_{1/2} = (1.4 - 1.6) \times 10^{21}$ yr was calculated.

Using the relation between the effective nuclear matrix element (NME) for $\varepsilon\beta^+2\nu$ decay: $(T_{1/2}^{\varepsilon\beta^+2\nu})^{-1} = G^{\varepsilon\beta^+2\nu} \cdot |M^{\varepsilon\beta^+2\nu}|^2$, and recent calculations of phase space factor $G^{\varepsilon\beta^+2\nu} = (702 - 741) \times 10^{-24}$ yr [30, 31], one can obtain a limit on NME for $\varepsilon\beta^+2\nu$ decay of ^{106}Cd to the ground state of ^{106}Pd as: $M^{\varepsilon\beta^+2\nu} < 1.1$.

We also used the data accumulated by the HPGe detectors to estimate limits on the 2β

processes in ^{106}Cd . For instance, in neutrinoless 2ε capture we assume that the energy excess is taken away by bremsstrahlung γ quanta with energy $E_\gamma = Q_{2\beta} - E_{b1} - E_{b2} - E_{exc}$, where E_{bi} is the binding energy of i -th captured electron on the atomic shell, and E_{exc} is the energy of the populated (g.s. or excited) level of ^{106}Pd . In case of transition to an excited level, in addition to the initial γ quantum, other γ 's will be emitted in the nuclear deexcitation process. For example, to derive a limit on the $2K0\nu$ capture in ^{106}Cd to the ground state of ^{106}Pd the energy spectrum accumulated with the HPGe detectors was fitted in the energy interval 2700 – 2754 keV by a simple function (first degree polynomial function to describe background plus Gaussian peak at the energy 2726.7 keV with the energy resolution $\text{FWHM} = 4.4$ keV to describe the effect searched for). The fit gives an area of the peak 6.2 ± 3.2 counts, with no evidence for the effect. According to [27] we took 11.4 events which can be excluded with 90% C.L. Taking into account the detection efficiency for γ quanta with energy 2726.7 keV in the experimental conditions (1.89%), we have set the following limit for the $2K0\nu$ capture of ^{106}Cd to the ground state of ^{106}Pd : $T_{1/2} \geq 4.2 \times 10^{20}$ yr. The excluded peaks are shown in Fig. 2 (right).

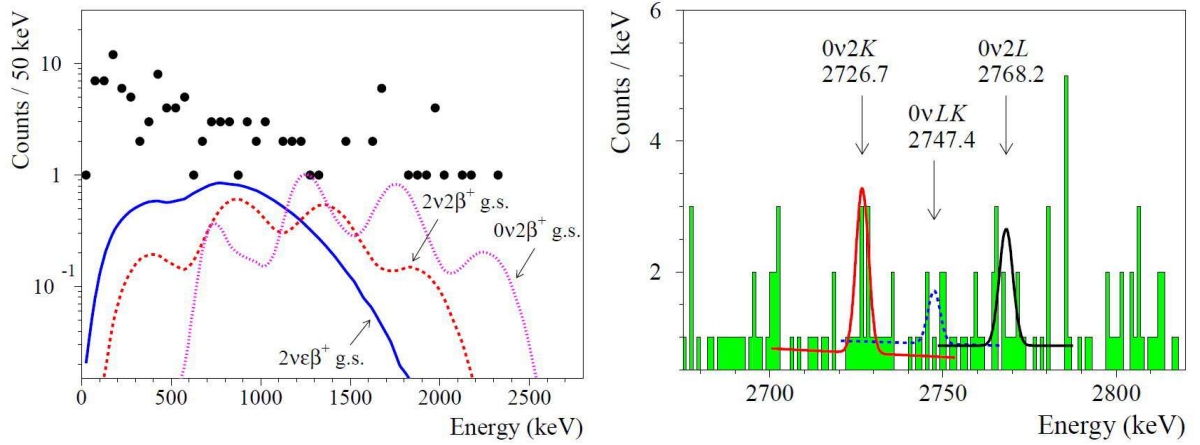


Figure 2. Left: Energy spectrum of the $^{106}\text{CdWO}_4$ detector during 13085 h in coincidence with 511 keV annihilation γ quanta in at least one of the HPGe detectors (filled circles). The excluded distributions of different 2β processes in ^{106}Cd are shown by different lines. Right: Part of the energy spectrum accumulated by the HPGe detectors. Excluded peaks expected in the $2K0\nu$, $KL0\nu$ and $2L0\nu$ captures in ^{106}Cd to the ground state of ^{106}Pd are shown.

Some of the obtained half-life limits on different 2β processes in ^{106}Cd are given in Table 1, where results of the most sensitive previous experiments are also given for comparison.

4. Conclusions

An experiment to search for 2β decay of ^{106}Cd with enriched $^{106}\text{CdWO}_4$ crystal scintillator with mass of 216 g in coincidence with four HPGe detectors has been completed after 13085 h of data taking. New improved limits on $2\beta^+/\varepsilon\beta^+/2\varepsilon$ processes in ^{106}Cd were set on the level of $T_{1/2} > 10^{20} - 10^{21}$ yr. The half-life limit on $\varepsilon\beta^+2\nu$ decay $T_{1/2} > 1.1 \times 10^{21}$ yr reached the region of some theoretical predictions. Advancement of the experiment in the version when $^{106}\text{CdWO}_4$ scintillator is operating in coincidence with two large volume radiopure CdWO_4 scintillation detectors in close (almost 4π) geometry is in progress.

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Table 1. $T_{1/2}$ limits on 2β processes in ^{106}Cd (AC – anticoincidence with HPGe; CC – coincidence with the given energy in HPGe; HPGe – using data of only HPGe detectors).

Decay and ^{106}Pd level (keV)	$T_{1/2}$ limit (yr) at 90% C.L.	
	Present work (data)	Best previous limit
$2\beta^+0\nu$, g.s.	$\geq 3.0 \times 10^{21}$ (CC 511 keV)	$\geq 1.2 \times 10^{21}$ [21]
$2\beta^+2\nu$, g.s.	$\geq 2.3 \times 10^{21}$ (CC 511 keV)	$\geq 4.3 \times 10^{20}$ [21]
$\varepsilon\beta^+0\nu$, g.s.	$\geq 1.5 \times 10^{21}$ (AC)	$\geq 2.2 \times 10^{21}$ [21]
$\varepsilon\beta^+2\nu$, g.s.	$\geq 1.1 \times 10^{21}$ (CC 511 keV)	$\geq 4.1 \times 10^{20}$ [28]
$\varepsilon\beta^+2\nu$, 0^+ 1134	$\geq 1.1 \times 10^{21}$ (CC 622 keV)	$\geq 3.7 \times 10^{20}$ [21]
$2K0\nu$, g.s.	$\geq 4.2 \times 10^{20}$ (HPGe)	$\geq 1.0 \times 10^{21}$ [21]
$2\varepsilon2\nu$, 0^+ 1134	$\geq 1.0 \times 10^{21}$ (CC 622 keV)	$\geq 1.7 \times 10^{20}$ [21]
Res. $2K0\nu$, 2718	$\geq 1.1 \times 10^{21}$ (CC 1160 keV)	$\geq 4.3 \times 10^{20}$ [21]
Res. $KL_10\nu$, 4^+ 2741	$\geq 8.5 \times 10^{20}$ (HPGe)	$\geq 9.5 \times 10^{20}$ [21]
Res. $KL_30\nu$, $2, 3^-$ 2748	$\geq 1.4 \times 10^{21}$ (CC 2236 keV)	$\geq 4.3 \times 10^{20}$ [21]

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